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INTEGRATION AND FLIGHT TEST OF AN OMEGA RECEIVER WITH THE P-3C AIRCRAFT NAVIGATION SYSTEM

by

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ABSTRACT

OMEGA is a very low frequency radio navigation system suitable for use by ships, aircraft and submarines. A network of four stations was established under the Navy's direction toward a final configuration of an eight station worldwide long range radio navigation system. As part of the Navy's development program for an airborne OMEGA navigation set, a receiver-converter was developed specifically to interface with the central computer in the P-3C aircraft, and provide a position update for geographic navigation. This paper will describe the P-3C OMEGA navigation integration and maintainability program for a production aircraft system, a flight test program, a laboratory replay program to give the capability of testing the various rate aiding sources, a laboratory silumation program to exercise the software mechanization over the parametric range of the variables, and present preliminary results from the flight test and the laboratory simulation.

BACKGROUND

Early in the Navy's development program for an airborne world-wide position fixing system it became apparent that OMEGA could satisfy this requirement for the P-3 aircraft. The P-3 aircraft is a land-based anti-submarine warfare (ASW) weapon system capable of a fifteen hour patrol mission and world-wide deployment.

During the mid sixties the Naval Research Laboratory (NRL) was in a research and development phase to demonstrate the capability of an airborne OMEGA navigation system and was resolving airborne integration problems with the MARK I, II and III systems (references 1 and 2). Concurrently the Naval Air Development Center (NAVAIRDEVCEN) was in the midst of the A-NEW development program for a new generation of P-3 aircraft (P-3C). This program was initiated to provide a Navy developed avionics system prior to airframe development. The A-NEW development cycle includes postulation of a system through study, refinement of the system through simulation, procurement of engineering prototype components, integration of the system through dynamic mockup, verification and evaluation of the system through flight tests, and development of equipment and software specifications.

An AN/ARN-88 (XN-1) airborne OMEGA navigation system was procured by the NAVAIRDEVCEN in conjunction with the then Bureau of Ships from ITT Federal Laboratories for evaluation as a position fixing system for the P-3C aircraft. The AN/ARN-88 was the first militarized airborne receiver. ITT Federal Laboratories built the interface to provide phase inputs to the central computer and rate aiding data to the AN/ARN-88. The NAVAIRDEVCEN developed a software program to process the phase data and provide a geographic position update. In 1967, prior to any flight testing of the system, a decision was made to terminate all AN/ARN-88 OMEGA development work on the A-NEW Program because of scheduling difficulties and the uncertainty of the equipment reliability and maintainability. A manual LORAN A/C set was added to the P-3C production system as an interim fixing aid until airborne OMEGA became available.

INTRODUCTION

The heart of the P-3C avionics system is the data processing system. The data processing system consists of the CP-901/ASQ-114 central computer, three logic units, two magnetic tape units, synchro conversion unit, manual entry subsystem (keysets), and general purpose display subsystem. The central computer has 65,536 words of core memory and sixteen input/output channels. The "P-3C Update Program" which expands the data processing system was brought about by the continuing increase in programming requirements and the desirability of non-essential core blocks to provide flexibility and backup. The expansion includes the addition of a 262,144 word drum memory and a fourth logic unit to provide central computer/drum interface and additional computer input/output channel capability.

The P-3C aircraft navigation system provides geographic navigation, ASW tactical navigation, steering, airways and terminal area guidance as well as display the navigation parameters. The system sensors are two inertial navigation sets (one set being utilized as a "hot backup"), a doppler radar set and a true airspeed computer. The inertial set provides north-south and east-west velocity and true heading to the central computer, which is the primary source for geographic navigation. The doppler radar set and true airspeed computer provide backup for geographic navigation. Tactical navigation is mechanized with inertial true heading and doppler velocity. Inertial velocity may be used in the event of doppler failure. Dead reckoning is performed in the central computer for geographic and tactical navigation. The essential difference in the two modes, geographic and tactical, is the method of compensating system error.

The AN/ARN-99 (V)1 OMEGA Navigation Set in the P-3C Update Program will provide a periodic position fix to compensate for errors in geographic navigation. The basic system integration philosophy is to reduce the Northrop Electronics Division developed receiver-computer, control indicator and antenna/coupler system to a receiver-converter and antenna/coupler system by using the P-3C central computer with the display and control functions.

P-3C OMEGA NAVIGATION INTEGRATION

The OMEGA navigation system was integrated into the geographic navigation system of the P-3C aircraft as a periodic position update to limit position error growth as a function of time and distance traveled (figure 1). The requirement for minimal changes to the existing geographic navigation software program and central computer loading restrictions dictated this integration approach.

The OMEGA function interfaces directly with the navigation sensors in the central computer. The status of navigation sensors is readily available to the OMEGA function and enables automatic re-selection of velocity and heading source in the event of sensor failure. Commonality in display and control functions with the P-3C system is accomplished by utilizing the NAV/COMM Operator's display and keyset. The P-3C Update OMEGA software program is initialized automatically using the date, time and present position entered during normal preflight operations. A

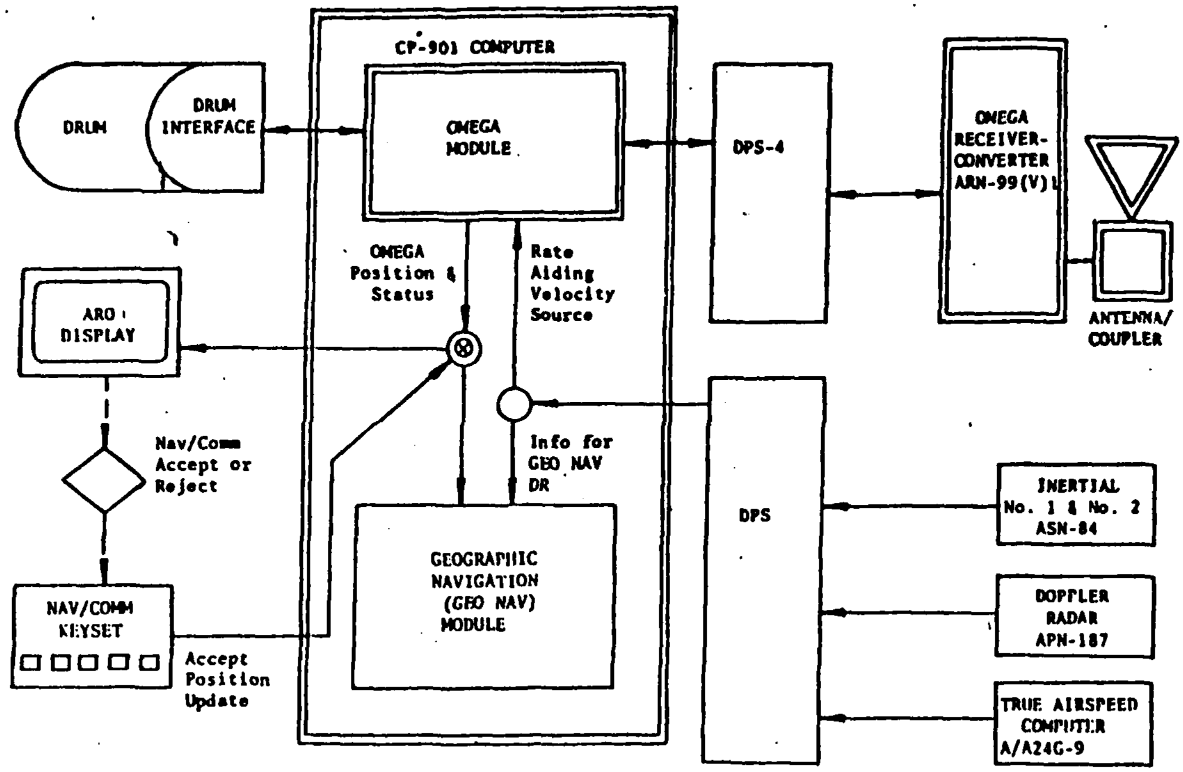

FIGURE 1

P-3C UPDATE OMEGA BLOCK DIAGRAM

dead reckoned position estimate is continuously available to the operator after stability has been reached. OMEGA position is represented by a direction cosine matrix which is updated with the selected velocity source and corrected with Kalman filter estimates of system error. A common operator function updates the geographic navigation system with position estimates from OMEGA, TACAN, Search Radar, etc.

The main emphasis in the design of the P-3C Update OMEGA Software Program was minimal execution time, even at the expense of a larger program size. The requirement for a periodic position update, such that the program remain activated for a short period of time and then deactivated, led to a partially active mode with the intent of reducing the execution load and decreasing the lag from initial activation to a valid OMEGA position fix. The partially active mode is mechanized by deactivating the propagation prediction routine and the measurement processing of the Kalman filter, which reduces the execution load. When in this mode the Kalman estimate of system errors grows and the variance of the error estimate deteriorates, but the data previously processed is not destroyed.

During a typical ASW mission, the operational use of OMEGA will commence when the NAV/COMM Operator initiates the navigation preflight functions. OMEGA will remain active from take-off to arrival of the aircraft in the operational area. Upon arrival "on station" the aircraft will begin an ASW mission. During the aircraft transit to the operational area, the geographic navigation position will be updated periodically by the NAV/COMM Operator who has the option to accept or reject the OMEGA position fixes. The NAV/COMM Operator will also compare the OMEGA position with the functionally independent inertial systems to evaluate the drift rate of each inertial system and select the best primary DR source. These man-machine relationships allow the NAV/COMM Operator to remain responsible for the quality of the aircraft navigation. The partially active mode of the OMEGA software program will be used when the ASW software modules place a high execution load on the central computer. At this time, only periodic activation of the full OMEGA function will be implemented to obtain a one time position fix. This operator selectable process will continue for the duration of the "on station" time. When the ASW operation is terminated, the aircraft will transit back to base with the OMEGA function active.

DESCRIPTION OF THE AN/ARN-99(V)1 HARDWARE

The antenna/coupler consists of a pair of orthogonal loops, with an active preamplifier for each loop, enclosed in an electrostatic shield. The antenna is designed for vertically polarized electromagnetic signal in the 10 to 14 KHz frequency range.

The receiver-converter, OR-90/ARN-99(V), consisting of seven modular assemblies and an interconnection box (figure 2), provides antenna lobe selection, generates precision frequencies for the local oscillator, generates calibration functions and processes three separate frequencies for conversion of phase data into a digital format for the central computer.

The central computer controls the antenna configuration through the antenna switching matrix by summing and phase shifting of the incoming signals on each frequency, and also provides control for test signal injection.

Each of the three receiver modules is a superheterodyne receiver with RF and IF sections to process the orthogonal loop antenna inputs. The receiver module provides gain, narrowband filtering for rejection of interfering

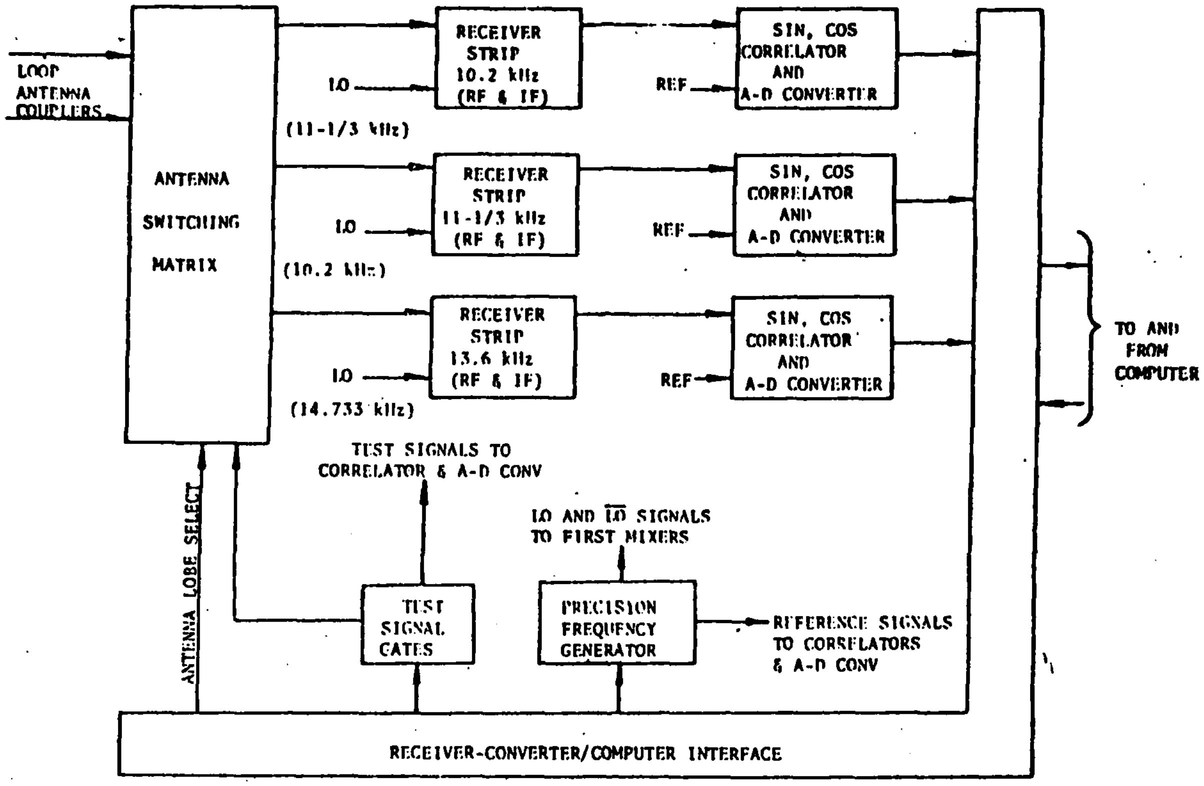

FIGURE 2

RECEIVER-CONVERTER BLOCK DIAGRAM

carriers, and dynamic limiting by the use of active filter techniques. The active filter technique provides phase stability for a wide dynamic range. The phase shift of each receiver over a 60 db range is less than ±0.5 centicycle and over a 100 db range is less than ±1.0 centicycle. Each RF amplifier is tuned to the appropriate frequency to provide bandpass filtering and limiting capability to reject an image with power levels up to 75 db. The amplifier heterodynes to an intermediate frequency common to each receiver strip. Each IF amplifier filter has an overall gain of 80 db at 200 Hz and a 77 db gain at band center.

The correlator and digital converter circuitry provide the initial phase measurement by forming a real-time product of the IF amplifier with the reference signal and the reference signal shifted by 90 degrees. The average products are sinusoidal functions, sine and cosine, of the phase difference of the two signals. The correlator output is converted to a pulse by an integrator and pulse generator which is maintained at zero output by means of feedback to the integrator. The pulse generator digital signal is then fed to the phase counter in the register, message, computer module. The register, message, computer module sums the digital sine and cosine inputs for each frequency and formats the data as three 30 bit parallel transfer words.

The required reference and test signals necessary to measure the phase are provided by the precision frequency generator circuitry which consists of a 10.608 MHz crystal oscillator and digital modulus counters used to divide down the crystal frequency. Frequencies generated are: 10.2, 11.33 and 13.6 kHz RF test signals, 10.2, 11.33 and 14.73 kHz local oscillator signals, 1.13 kHz IF signal and 176.8 kHz timing signal. The crystal oscillator provides stability of five parts in 10^8 per week and four parts in 10^7 long term within five minutes of power application.

Communication from the central computer to the receiver-converter is provided by the converter, digital to digital module. This module enables external function commands from the central computer for antenna switching and receiver-converter group testing. The external function command format is two, 12 bit, independent commands per 30 bit parallel transfer.

The power supply regulates the dc voltages for the receiver-converter and the antenna/coupler from the 115V rms 400 Hz single phase aircraft power. The interconnection box provides circuit connections between modules, receiver-converter to aircraft cabling and the mechanical interface for the plug-in modules.

DESCRIPTION OF THE P-3C UPDATE OMEGA SOFTWARE

The P-3C Update OMEGA software (figure 3) is an outgrowth of the AN/ARN-99 receiver-computer software program developed by Northrop Electronics Division. The design philosophy has been to simplify the hardware to reduce system complexity, production cost, and maintain performance by providing software compensation and calibration. This approach complicates the software program but at the same time allows for commonality in the navigation system control with better systems integration and versatility.

The OMEGA program is initialized with a dead reckoned position and corrected with Kalman processed OMEGA phase data. Aircraft position is calculated using an rho-rho or circular solution as opposed to the normal hyperbolic

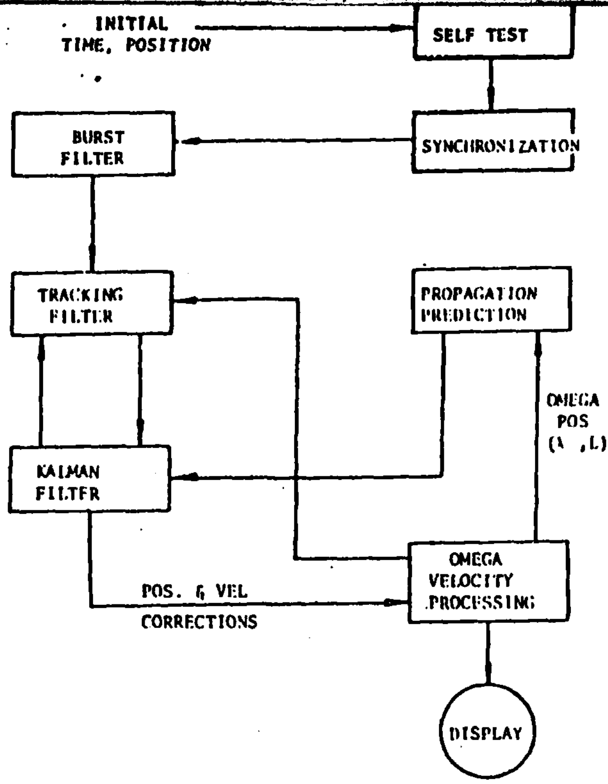

FIGURE 3

P-3C UPDATE OMEGA SOFTWARE PROGRAM

solution. After activation the central computer performs the self test routine. This routine is designed to perform a functional GO/NO-GO test of the receiver-converter hardware and central computer interface. The details of this test routine will be discussed later.

Synchronization with the OMEGA station transmission pattern is then established. Synchronization is determined by processing the input data over a ten second period with 100 different start times for the transmission pattern. The differential correlation values for the start times are compared against a confidence criteria to establish synchronization.

The phase data is processed to form a phase measurement from individual stations. The burst filter phase measurement, referenced to the receiver oscillator, is in error due to fluctuations of receiver phase shift, scale factor and bias. These errors are calculated and compensated for by utilizing hardware reference signals during alternate non-transmission times (slots). For the statistical filters which follow (Tracking and Kalman), it is necessary to obtain a confidence value (phase variance) for each phase measurement. The phase variance is computed by comparing the burst signal with the noise level during alternate slots.

The tracking filters receive the burst phase measurement and phase variance for each frequency at the end of each transmission period. There are twenty-four distinct tracking filters, one for each of the three frequencies on each of the eight OMEGA stations. In addition to the burst filter inputs of phase and phase variance, there is velocity and heading to provide an estimate of phase rate relative to the stations due to aircraft motion. The velocity source is operator selectable and can be inertial, doppler, true airspeed or no rate aiding. The estimates of phase and phase rate are used to update the individual tracking filters. The tracking filter also estimates the phase rate error to correct the computed phase rate derived from the rate aiding source. In addition to computing estimated phase and phase rate error, each tracking filter computes the variance of the estimated phase, the variance of the estimated phase rate error, and the co-variance of estimated phase and phase rate error. These measurements, errors and variances are then combined with the phase and phase variance measurements of the burst filter to statistically determine a single phase estimate and confidence value for the tracking filter every ten seconds. This confidence value is compared with a constant to determine if the single phase estimate is acceptable for the Kalman filter. If the acceptance criteria are not met, additional burst filter measurements will be combined with the tracking filter until the criteria are satisfied. When data is transferred to the Kalman filter, the tracking filter's estimates are reinitialized and the process repeats (as well as the reader).

The propagation prediction routine provides the predicted phase measurement to the Kalman filter. This predicted phase measurement is based on the best estimate of present position, date, time of day and station location. The propagation prediction routine is a real-time mathematical model based on work performed by the Naval Electronics Laboratory Center and the Northrop Electronics Division (reference 4). The model accounts for diurnal effect, ground conductivity, earth's magnetic field and latitude effects. The predicted phase velocity is calculated to include propagation effects by determining where the aircraft is located with respect to the transmission stations, where the sun is located with respect to the great circle paths between the aircraft and stations, the conductivity of earth surfaces under the great circle paths, the path angle of intersection to the earth's magnetic field and the latitude of the great circle path between the aircraft and the transmission stations.

The Kalman filter receives inputs of the single phase estimate and confidence value from the individual tracking filters, and the predicted phase and phase variance from the propagation prediction routine. The single phase estimate from the tracking filter and the predicted phase value generated from the propagation prediction routine as a function of aircraft position are differenced to generate the "measurement system error." The Kalman residual is formed by the difference between the "measurement system error" and the Kalman estimate of system error. This residual and the weighting matrix are used by the Kalman filter to update its estimate of position and velocity error, oscillator drift and start time, and errors in the diurnal model. In addition, the estimate of system "goodness," the covariance matrix, is updated to reflect the inclusion of the new measurement. The Kalman filter also predicts in the time-update routine how the system errors will grow as a function of time, and also how the variance of the system deteriorates with time. The estimate of variance is then used to determine the optimum weighting for subsequent measurements.

MAINTENANCE PHILOSOPHY

World-wide deployment of P-3C aircraft with limited shop level maintenance support increases the need for system maintenance to be performed on the aircraft. Central computer controlled system testing has decreased shop level maintenance. This maintenance philosophy was employed in the design of the OMEGA equipment. The specified maintenance requirement for the OMEGA equipment is to detect and localize at least 95% of all failures and to perform all corrective maintenance actions on the aircraft in less than 30 minutes (maximum) for at least 90% of the failures.

Computer controlled equipment testing consists of two levels - System GO/NO-GO (SYGNOG) and diagnostic. SYGNOG tests performed by the computer are primarily a fault detection test to determine system readiness. The SYGNOG software program is used as a preflight and postflight check of equipment status. If a fault is detected in a weapon system functional area the diagnostic program for this equipment is initiated by the operator. The diagnostic program is designed to isolate equipment failure to a light replaceable assembly (LRA) easily removed and replaced. The LRA's of the OMEGA receiver-converter consists of seven functional modules. The self test routine of the OMEGA software module forms the basis of both SYGNOG and diagnostic programs for OMEGA. The diagnostic program includes additional programming to indicate either a specific LRA to be replaced or the test points to be checked to determine the faulty LRA. The self test routine includes coherence status check, rf test of each receiver section, phase angle to digital test for each of the three frequencies and a phase counter test. These tests are initiated by the central computer which also processes the data to be compared with established acceptance criteria.

Software and hardware testing with the engineering prototype OMEGA receiver-converter has disclosed the desirable as well as deficient maintenance features of the equipment. The production equipment specification guards against a recurrence of these deficiencies and amplifies the desirable maintenance features. Changes in equipment design such as easier removal of functional modules, addition of test points to increase in situ aircraft diagnostic capability, and revised packaging for better access will be incorporated into the production equipment.

FLIGHT TEST DESCRIPTION

The flight testing was performed on the U.S. Navy AUTEC (Atlantic Undersea Test and Evaluation Center) range with the purpose of collecting OMEGA navigation data for analysis and evaluation. OMEGA phase data was also collected and will be utilized with the OMEGA replay program described later. The OMEGA navigation data utilized in the analysis was collected on three separate days: 18, 19 and 20 February 1971. Flight profile geometry for these days ranged from straight and level flight with constant velocity, to a figure eight, a race track and a box. The latter three geometries represent typical flight maneuvers encountered during anti-submarine warfare missions.

The OMEGA navigation data was recorded on magnetic tapes while the aircraft was tracked by the ground radar range. Aircraft events were synchronized with the range by an on board time code generator which was keyed by a coded signal transmitted by the range. Each event recorded on the aircraft was tagged with time supplied by the time code generator. As information was being recorded from all the rate aiding velocity sources and the burst filter, the OMEGA program was exercised to run with different stations and rate aiding sources. The OMEGA navigation data recorded during the flight testing included four, three and two station solutions, with inertial and air mass velocities as rate aiding sources. The OMEGA program was also run with no rate aiding source. Problems with the doppler radar hardware and software program did not permit the OMEGA program to run with doppler velocity as a rate aiding source. Anomalies observed in the data have been successfully identified with propagation anomalies known to affect OMEGA position accuracy. All other large errors have been correlated with equipment problems, software program failures or low signal strength received from one or more of the stations.

LABORATORY REPLAY PROGRAM

In order to derive optimum use of the OMEGA navigation data collected on the AUTEC range a laboratory replay program was developed. The OMEGA flight test program in the aircraft records the measured phase (for each station) from the burst filter, velocities from the rate aiding sources and ZULU time. The OMEGA Replay program (figure 4) was designed to operate with any combination of OMEGA stations and velocity sources. The computer replay program aircraft position is compared with the AUTEC recorded position to determine the OMEGA position accuracy.

Analysis utilizing the replay program is particularly interested in determining for each velocity source and number of stations available, when the OMEGA position error has stabilized and the expected error at stability. This is an important consideration if the OMEGA position is to periodically bound the errors of the geographic navigation system.

A limited amount of data has been obtained for the laboratory replay program. Future analysis will cover such questions as the time for the OMEGA program to reach stability as a function of the rate aiding source and the number stations, and the accuracy at stability for each case.

SOFTWARE SIMULATION

A laboratory software simulation technique has been developed to facilitate debugging of the many mathematical filters in the OMEGA program (figure 5). The OMEGA program may be exercised over the entire dynamic range of the parameters without flight testing each parameter individually. The simulation program utilizes a navigation mathe-

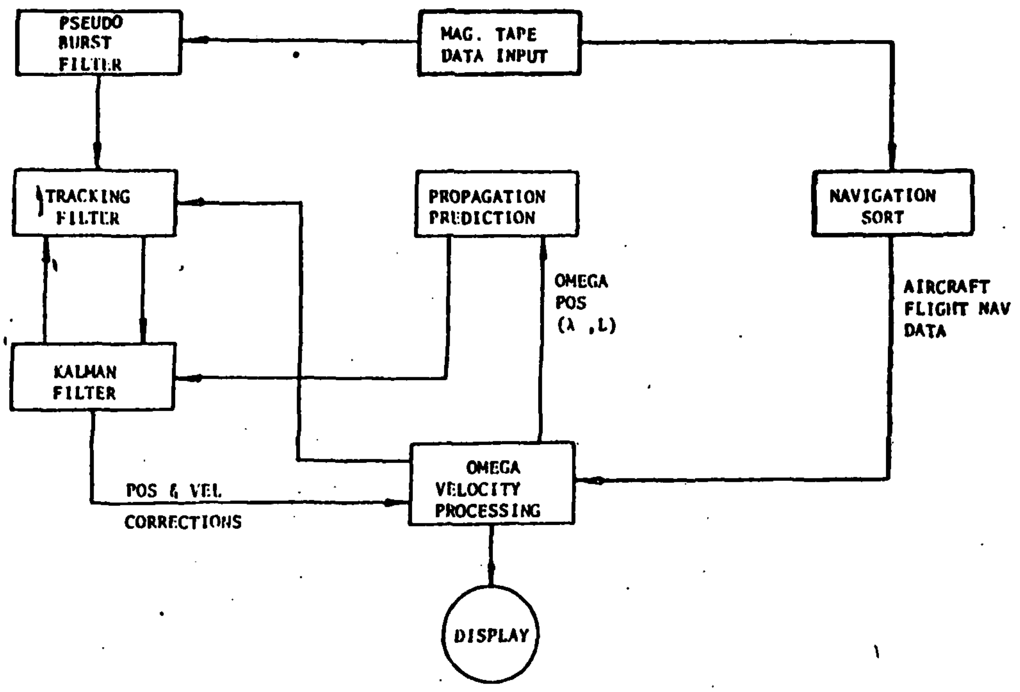

FIGURE 4

OMEGA LABORATORY REPLAY PROGRAM

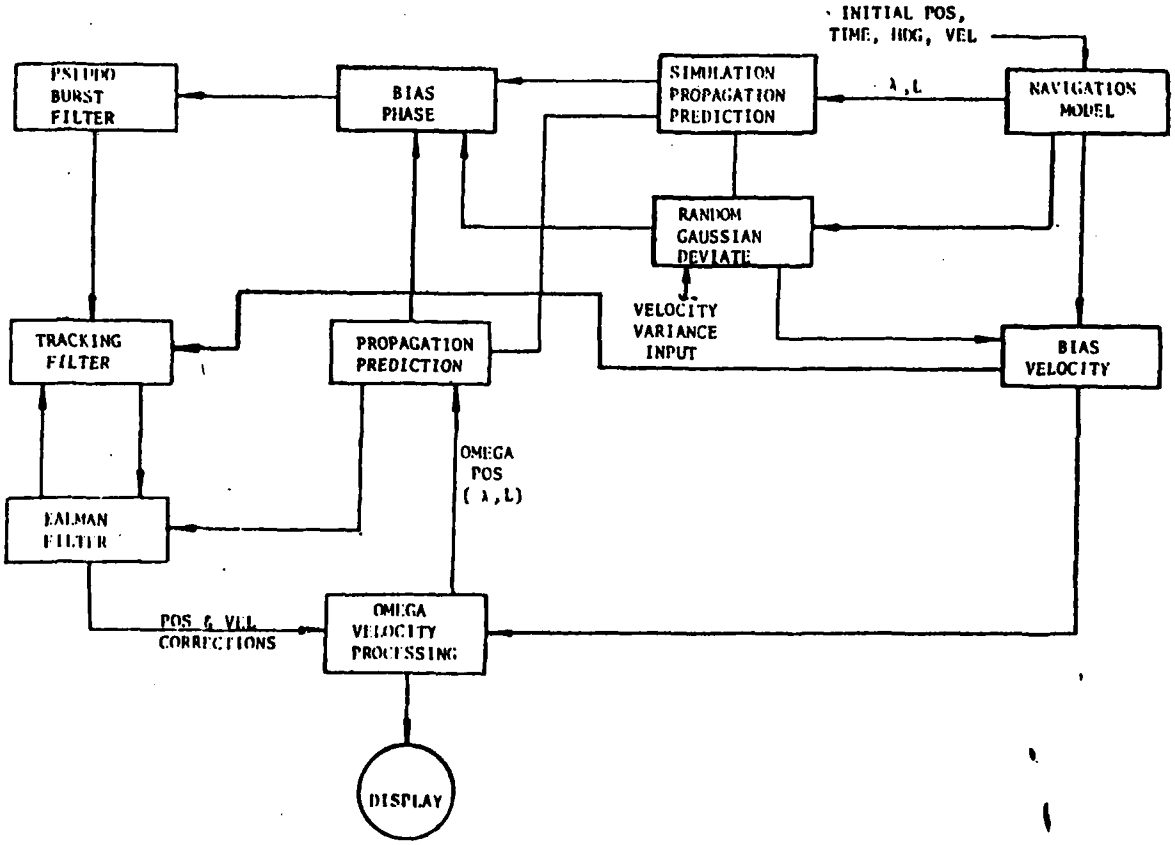

FIGURE 5

OMEGA LABORATORY SIMULATION PROGRAM

mathematical model which generates aircraft navigation system dead reckoned position, and a random gaussian deviate routine which generates errors for OMEGA phase and velocity.

In operating the software simulator a dead reckoned position from the navigation model and the time of day are entered into the simulation propagation prediction routine which generates a phase and phase variance. The next two routines in the simulation process allow for adding a random and/or bias error to OMEGA phase and navigation velocity. The phase and phase variance are inputted into the gaussian deviate routine and a random phase error is derived from a normal distribution having a mean and variance equal to the calculated phase and variance. This random phase error is added to the mean of the phase and inputted to the phase bias routine. The phase bias routine adds a phase bias error which simulates the oscillator drift of the OMEGA receiver hardware. The gaussian deviate routine also accepts aircraft velocity and a constant variance based on the velocity source selected from the navigation model and adds a random velocity error. This velocity is then inputted to the bias velocity routine which adds a bias error to the velocity. These simulated values represent either inertial velocity, doppler velocity, air mass or no velocity source.

Having completed the simulation process these errored values of phase and phase variance, and velocity are inputted into the OMEGA program tracking filter as an estimate of the phase measurement. The random and bias errored velocity is also inputted into the OMEGA velocity processing routine. Simulated true heading from the navigation model is inputted to both the tracking filter and OMEGA velocity processing routines.

The random number generator used was obtained from the IBM 360 scientific subroutine package, Version III, and adapted for a 30 bit word. The input values required for the subroutine are the mean, the standard deviation and the numbers 1, 2, 3, 4, 5, 6, and 7. The bias generator adds a constant to both phase and velocity when desired. Phase bias is obtained by the following equation:

$$\phi'' = \phi' (1 - \beta_{t_0} \Delta t)$$

where ϕ' is the phase derived from the random number generator. Velocity bias is obtained from a similar equation:

$$V'' = V' (1 - \beta_t \Delta t)$$

where the bias for each velocity source is 2/3 nautical miles/hour drift for inertial and doppler velocities, 2 nautical miles/hour drift for air mass velocity and no rate aiding.

Representative runs which compare a simulated run with flight data are shown in figure 6 (inertial-three station-constant velocity and heading). Good correlation and similar trends can be seen from the simulated and actual flight error plots.

ANALYSIS

The analysis of system capability was performed by using the data obtained from the AUTEC flight tests. Samples of OMEGA derived positions and rate aiding velocities were extracted on to the aircraft's magnetic tape every 20 seconds. Sample data for the analysis was selected when the Kalman filter and the time varying error function of position and velocity had stabilized. It was assumed, because of the Kalman filter, that each successive sample of

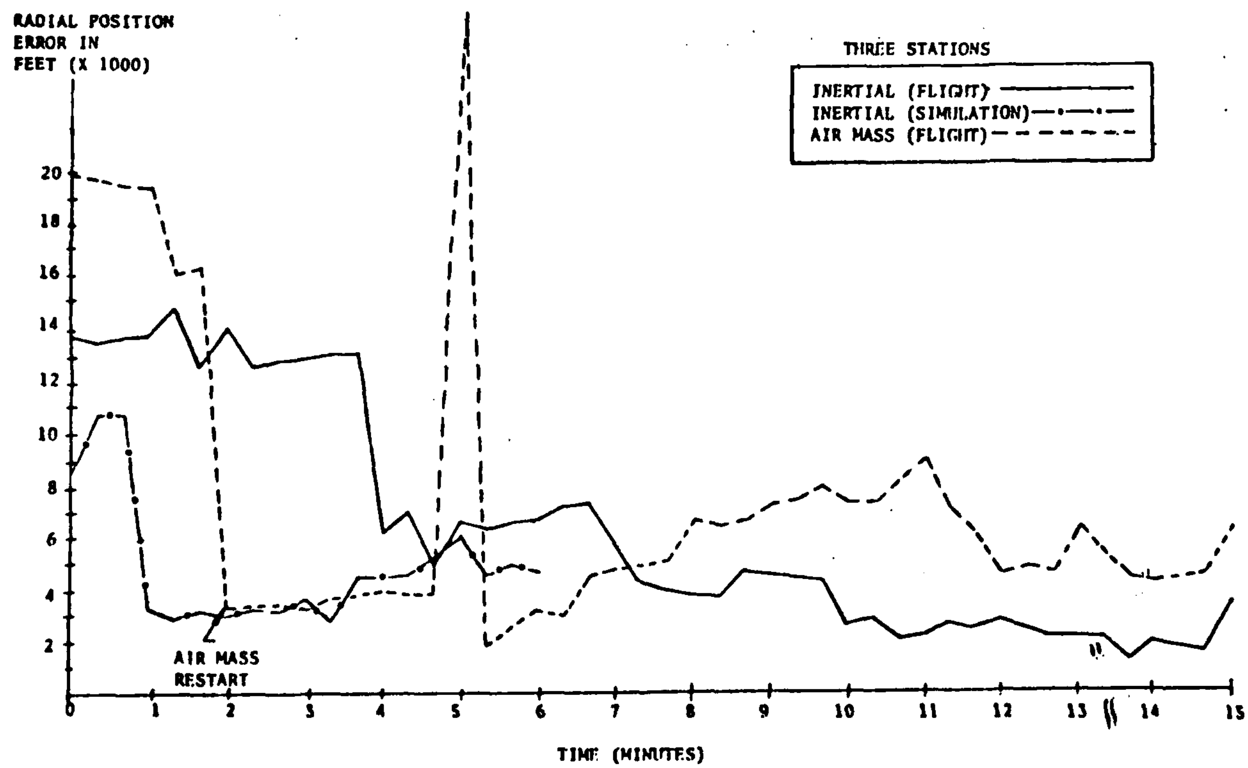

FIGURE 6
RADIAL POSITION ERROR (RESTART RESPONSE)

position and velocity is correlated with previous samples. A "run" is defined as a single passage of the aircraft past the AUTEC tracking range. Each run represents a given "mode of operation" corresponding to the number of received stations and the preselected rate aiding source. A run with a given mode is usually 15 minutes in duration and will contain approximately 45 samples. The sample data contained at least one run for each mode of operation. If multiple runs were made for any one mode, each run was considered to be statistically independent. If only a single run existed for a given mode, the run was separated by deleting specified time segments which segmented the data in such a manner as to assure the statistical independence of the segments.

Evaluation of the sample mean, the variance of the sample mean, and the variance of the time varying function was performed under the following assumptions - the error functions are stationary, and are ergodic. The first assumption is consistent with the condition in which sample data is only accepted for analysis after the Kalman filter has reached stability. The latter assumption states that the mean of the ensembles is equivalent to the mean of the time varying function and similarly for the mean square value. With these assumptions accepted, the mean, variance about the mean, and variance of the time varying function can be calculated (reference 4). The analysis utilizes a given set of runs with the same conditions: e.g., three stations received, inertial velocity as the rate aiding source, and a sample of the time varying function (figure 6) every twenty seconds. A matrix was created by stacking each of the runs, and the ensemble was defined by the column of random variables (each error amplitude), where each sample in the ensemble was independent. The mean of the ensembles "m" is then defined as

$$m = \frac{1}{n}(\bar{\zeta}_1 + \bar{\zeta}_2 + \dots + \bar{\zeta}_n)$$

and the mean of each ensemble $\bar{\zeta}_i$ is computed from the following:

$$\bar{\zeta}_i = \frac{1}{N}\sum_{k=1}^{N} a_k^i \qquad i = 1, 2, \dots, n$$

where a_k^i is the error "a" in the ith column kth row.

The variance of the time varying function σ_f^2 is computed from the following

$$\sigma_f^2 = \overline{\phi_{ff}(0)} - m^2$$

where the autocorrelation function $\phi_{ff}(0)$ is computed from independent samples and is

$$\phi_{ff}(0) = \frac{1}{N}\sum_{k=1}^{N}(a_k)^2$$

For "n" columns there are "n" values of $\phi_{ff}(0)$ and the simple average is computed.

The variance about the mean σ_m^2, which will determine if a bias exists in any of the random variables, is computed from the following:

$$\sigma_m^2 = \sum_{k=-(n-1)}^{(n-1)} \frac{n-|k|}{n^2}\left(\phi_{ff}(kL) - m^2\right)$$

where L is the time difference between samples and k = (ith column - jth column), and there are "n" columns to evaluate. In each column there are "N" values. Consider the crosscorrelation of column 1 and column 2. This relationship is evaluated by

$$\phi_{ff}(L) = \overline{\zeta_1 \zeta_2} = \frac{1}{N}\sum_{k=1}^{N} a_k^1 a_k^2$$

There are 2(n-1) values of $\phi_{ff}(L)$ to evaluate and average. This is accomplished for all values of $\phi_{ff}(kL)$ in order to evaluate the variance about the mean.

As expected for large samples, multiple runs, the standard deviation about the mean is less than the standard deviation about the time varying function f(t). If independent successive samples were assumed the variance about the mean is

$$\sigma_m^2 = \frac{\sigma_f^2}{n}$$

or the normalized variance about the mean would be proportional to the reciprocal of the number of rows.

The mean and variances are now computed for the following error measurements:

Latitude Error (ft)

$$\Delta L = (L^\circ \text{ Aircraft} - L^\circ \text{ AUTEC})\frac{R\pi}{180^\circ}$$

where R is the mean radius of the earth

Longitude Error (ft)

$$\Delta l = (l^\circ \text{ Aircraft} - l^\circ \text{ AUTEC})\frac{R\pi}{180^\circ}\cos L \text{ AUTEC}$$

The radial error (ft)

$$\text{RADIAL ERROR} = (\Delta L^2 + \Delta l^2)^{1/2}$$

The transformation from the OMEGA coordinate system to the geographical coordinate system is performed to derive the north and east velocities, V_N and V_E are

$$V_N = (a_1 \cos\theta + a_2 \sin\theta)$$

$$V_E = (-a_1 \text{ SIN } \theta + a_2 \text{ COS } \theta) \text{ R COS L AUTEC}$$

where a_1 and a_2 are the velocities in the OMEGA coordinate system and θ is the wander azimuth angle.

The velocity errors north V_N and the velocity error east V_E are

$$\Delta V_N = V_N - V_{N,\text{ AUTEC}}$$

$$\Delta V_E = V_E - V_{E,\text{ AUTEC}}$$

The radial velocity error

$$\Delta V_R = (\Delta V_N^2 + \Delta V_E^2)^{1/2}$$

Errors in position and velocity are also resolved in the coordinate axis defined along and across the heading of the aircraft. The along track error

$$\Delta A.T. = \Delta l \text{ SIN H} + \Delta L \text{ COS H}$$

The cross track error

$$\Delta C.T. = \Delta l \text{ COS H} - \Delta L \text{ SIN H}$$

where H is the aircraft track angle defined by the tracking range. The error in velocity along track

$$\Delta V(A.T.) = \Delta V_E \text{ SIN H} + \Delta V_N \text{ COS H}$$

The error in velocity across track

$$\Delta V(C.T.) = \Delta V_E \text{ COS H} - \Delta V_N \text{ SIN H}$$

The OMEGA error measurements will be evaluated using the described statistics.

No attempt is made at this time to determine the correlation between axes in the geographic coordinate system or in the aircraft coordinate system, one would expect a high degree of correlation due to a rho-rho position solution (reference 5).

OMEGA SYSTEM ACCURACY

The data recorded during the three days on the AUTEC range was mostly straight and level runs with inertial (INS), air mass and no rate aiding (N.R.A.) as velocity source and with the number of stations used varying from two to four. Not all combinations were exercised but isolated cases of changing geometry and acceleration are analyzed. Results of the analysis are presented below.

TABLE I

POSITION ERROR - GEOGRAPHIC COORDINATE SYSTEM

	INS 4 STATIONS		INS 3 STATIONS		AIR MASS 3 STATIONS		AIR MASS 2 STATIONS		N. R. A. 4 STATIONS	
	MEAN $\pm\sigma_m$	σ_f	MEAN $\pm\sigma_m$	σ_f	MEAN $\pm\sigma_m$	σ_f	MEAN $\pm\sigma_m$	σ_f	MEAN $\pm\sigma_m$	σ_f
LATITUDE ERROR (FT)	136.0 ±2160.0	2340.0	1901.3 ±1962.9	2337.9	646.3 ±498.4	4159.0	-1596.7 ±2453.2	4621.6	4541.0 ±2817.1	6243.7
LONGITUDE ERROR (FT)	2332.0 ±5777.7	6045.8	3442.0 ±2610.5	3340.1	4565.7 ±1628.3	3336.5	-3483.9 ±2674.8	8517.2	16471.9 ±6469.9	12397.4
RADIAL ERROR (FT)	6292.3 ±2198.9	2809.5	5019.1 ±2057.7	2688.9	5794.4 ±597.1	4015.3	8399.1 ±948.4	6167.8	18396.5 ±5670.3	12091.1

The position errors in the geographic coordinate system for all straight and level runs are listed in table I. The standard deviation for the longitudinal error, resolved by the Hawaii station, is consistently larger than the standard deviation for the latitude error. The degradation of accuracy in the longitudinal axis is caused by the few number of measurements from the Hawaii station relative to all other stations. In general, accuracy increases as the quality of the velocity source improves and as the number of stations used increases. Better accuracy would have been obtained for the INS-four station mode, but a high drift in the inertial system used degraded the accuracy. The number of runs utilized in analyzing each mode is given in table II. The velocity errors in the geographic coordinate system are tabulated in table III. A smaller velocity error can be observed with increasing number of stations, due to redundant measurement in the rho-rho solution. Errors in the aircraft coordinate system are tabulated in table IV. The accuracy again improves as the quality of the velocity source and the number of stations increase.

To determine if accuracy is affected by aircraft heading, runs that have the same heading are grouped and analyzed in table V. For the INS-three station mode a significant mean position error in latitude can be observed when the aircraft is heading in a southern direction. This is a south position bias. When the aircraft's heading north the bias is reflected with a negative mean. Although not as obvious because of larger errors, a similar trend can be seen

TABLE II

NUMBER DATA POINTS - STRAIGHT AND LEVEL

	RUNS	NUMBER OF DATA POINTS	TOTAL TIME (MINUTES)
INS - FOUR STATIONS	2	94	28.2
INS - THREE STATIONS	7	378	113.4
AIR MASS - THREE STATIONS	1	40	12.0
AIR MASS - TWO STATIONS	2	94	28.2
N.R.A. - TWO STATIONS	1	58	17.4

TABLE III

VELOCITY ERROR - GEOGRAPHIC COORDINATE SYSTEM

	INS 4 STATIONS		INS 3 STATIONS		AIR MASS 3 STATIONS		AIR MASS 2 STATIONS		N. R. A. 4 STATIONS	
	MEAN $\pm\sigma_m$	σ_f	MEAN $\pm\sigma_m$	σ_f	MEAN $\pm\sigma_m$	σ_f	MEAN $\pm\sigma_m$	σ_f	MEAN $\pm\sigma_m$	σ_f
LATITUDE VELOCITY ERROR (KNOTS)	-1.151 ±1.833	3.146	-1.904 ±3.347	3.879	-0.501 ±2.461	3.580	0.420 ±8.882	4.788	17.934 ±27.682	63.369
LONGITUDE VELOCITY ERROR (KNOTS)	-7.450 ±0.695	1.825	0.540 ±5.560	5.707	-8.958 ±2.429	2.926	3.776 ±7.448	9.080	- 0.347 ±17.148	55.293
RADIAL VELOCITY ERROR (KNOTS)	8.184 ±0.085	1.756	6.850 ±1.494	2.147	9.817 ±1.889	2.347	9.425 ±2.782	5.566	67.416 ±21.606	53.383

TABLE IV

POSITION AND VELOCITY ERROR - AIRCRAFT COORDINATE SYSTEM

	INS 4 STATIONS		INS 3 STATIONS		AIR MASS 3 STATIONS		AIR MASS 2 STATIONS		N. R. A. 4 STATIONS	
	MEAN $\pm\sigma_m$	σ_f	MEAN $\pm\sigma_m$	σ_f	MEAN $\pm\sigma_m$	σ_f	MEAN $\pm\sigma_m$	σ_f	MEAN $\pm\sigma_m$	σ_f
ALONG TRACK POSITION ERROR (FT)	-748.8 ±188.4	780.6	-1821.9 ± 500.4	1135.9	-973.5 ±880.5	4883.3	-1568.3 ± 563.6	1809.0	-1514.7 ±2897.9	5388.9
ACROSS TRACK POSITION ERROR (FT)	2271.5 ±6147.8	6415.3	-1793.4 ±4393.4	4959.4	4508.8 ±1454.6	2138.8	-3259.2 ±3806.2	9603.9	17024.5 ±6388.9	12785.1
ALONG TRACK VELOCITY ERROR (KNOTS)	1.236 ±2.144	3.266	5.155 ±0.889	1.995	2.637 ±2.149	3.052	1.281 ±0.591	3.693	21.257 ±29.842	62.300
ACROSS TRACK VELOCITY ERROR (KNOTS)	-7.404 ±0.077	1.744	-3.606 ±2.432	2.824	-8.584 ±2.690	3.453	-7.384 ±3.722	7.072	-4.947 ±19.776	5.103

TABLE V

POSITION AND VELOCITY ERROR - GEOGRAPHIC COORDINATE SYSTEM

(NORTH-SOUTH RUNS)

	INS 3 STATIONS NORTH		INS 3 STATIONS SOUTH		A.M.- 2 STATIONS NORTH		A.M.- 2 STATIONS SOUTH	
	MEAN $\pm\sigma_m$	σf	MEAN $\pm\sigma_m$	σf	MEAN $\pm\sigma_m$	σf	MEAN $\pm\sigma_m$	σf
LATITUDE ERROR (FT)	-659.5 $\pm$879.1	1643.3	2925.6 $\pm$1182.7	1767.5	-4627.0 $\pm$4369.4	4490.4	922.4 $\pm$3008.0	3313.5
LONGITUDE ERROR (FT)	3971.2 $\pm$2900.1	3473.7	3230.2 $\pm$2456.4	3332.7	-7200.1 $\pm$8907.3	8971.4	- 421.2 $\pm$6578.9	7106.3
RADIAL ERROR (FT)	4788.5 $\pm$2211.8	2735.7	5111.3 $\pm$1985.1	2664.4	10276.4 $\pm$8178.5	8264.5	7613.4 $\pm$1898.2	2131.3
LATITUDE VELOCITY ERROR (KNOTS)	3.329 $\pm$0.52	1.959	-3.997 $\pm$0.492	2.049	0.501 $\pm$3.157	4.395	1.042 $\pm$2.539	4.852
LONGITUDE VELOCITY ERROR (KNOTS)	-7.721 $\pm$0.507	1.148	3.845 $\pm$0.225	2.616	-2.830 $\pm$4.884	5.30	10.670 $\pm$2.294	4.600
RADIAL VELOCITY ERROR (KNOTS)	8.662 $\pm$0.296	0.911	6.125 $\pm$1.119	2.070	-6.095 $\pm$3.347	4.302	11.780 $\pm$2.520	4.588

TABLE VI

POSITION AND VELOCITY ERROR - GEOGRAPHIC COORDINATE SYSTEM

(DIFFERENT FLIGHT CONFIGURATIONS)

	INS 3 STATIONS STRAIGHT FLIGHT		INS 3 STATIONS FIGURE 00		INS 3 STATIONS RACE TRACK		INS 4 STATIONS ACCELERATION		INS 4 STATIONS BOX FLIGHT	
	MEAN $\pm\sigma_m$	σf	MEAN $\pm\sigma_m$	σf	MEAN $\pm\sigma_m$	σf	MEAN $\pm\sigma_m$	σf	MEAN $\pm\sigma_m$	σf
LATITUDE ERROR (FT)	1901.3 $\pm$1960.9	2337.9	75.2 $\pm$986.9	1595.0	3112.5 $\pm$1229.3	1432.1	-1123.0 $\pm$ 960.4	1178.7	542.7 $\pm$956.2	1469.9
LONGITUDE ERROR (FT)	3442.0 $\pm$2612.5	3390.1	1655.8 $\pm$806.5	1460.8	7899.0 $\pm$3386.1	3533.4	668.6 $\pm$2228.8	2326.3	1004.7 $\pm$1670.8	1885.3
RADIAL ERROR (FT)	5019.1 $\pm$2057.7	2688.9	2510.7 $\pm$518.5	1059.1	8535.3 $\pm$3581.6	3710.9	2665.7 $\pm$1040.2	1184.6	2288.5 $\pm$963.2	1332.7
LATITUDE VELOCITY ERROR (KNOTS)	-1.904 $\pm$3.347	3.879	-0.329 $\pm$1.458	4.580	0.364 $\pm$0.501	6.144	3.093 $\pm$1.861	3.212	-2.17 $\pm$0.738	2.510
LONGITUDE VELOCITY ERROR (KNOTS)	0.540 $\pm$5.560	5.707	1.304 $\pm$2.793	14.001	2.433 $\pm$2.678	24.458	-4.224 $\pm$2.144	2.725	1.830 -8.663	13.692
RADIAL VELOCITY ERROR (KNOTS)	6.850 $\pm$1.494	2.147	13.358 $\pm$0.387	6.353	17.358 $\pm$6.696	18.458	6.499 $\pm$0.822	1.707	12.506 $\pm$0.803	6.739

in the air mass-two station mode. It is interesting to note, although the data was separated, that the standard deviation of the time varying function about the radial error is consistent, being 2735.7 ft in the northern direction, 2664.4 ft in the southern direction and 2688.9 ft for non-heading correlated data.

Accuracies in the geographic coordinate system for different flight configurations are tabulated in table VI. For each of the flight geometries table VII lists the number of data points used to analyze the data. Each of these runs was segmented to give statistically independent segments from which the variance about the mean and time varying function was calculated. No significant degradation in position is observed for each of the maneuvering flight paths. There is a significant increase in the velocity variances about each axis for all maneuvers with the exception of the aircraft accelerating. Again, significant bias errors and higher variances about the time varying functions are observed in the longitudinal axis, and are attributed to poor signal strength resolving that axis.

While on the range there were only two restarts of the OMEGA program: INS-three station mode and air mass-three station mode. The radial errors are plotted in Figure 6, with the flight data and a simulated restart of the INS-three station mode. Stability for the flight data occurs at approximately three minutes for both the INS-three station run and the air mass-three station run. The stability for the simulated laboratory program occurred at approximately one minute.

TABLE VII

NUMBER DATA POINTS - DIFFERENT FLIGHT CONFIGURATIONS

	RUNS	NUMBER OF DATA POINTS	TOTAL TIME (MINUTES)
INS - THREE STATIONS FIGURE EIGHT	1	103	30.9
INS - THREE STATIONS RACE TRACK	1	54	18.0
INS - FOUR STATIONS ACCELERATION	1	59	14.7
INS - FOUR STATIONS BOX FLIGHT	1	138	41.4

SUMMARY

The OMEGA navigation system has been integrated into the P-3C Update aircraft as a periodic position update for the generic navigation system. The OMEGA system has been mechanized to reduce system complexity, simplify hardware and gain commonality in the P-3C navigation routines, by utilizing a receiver-converter and central computer software program. When the OMEGA program is deactivated to reduce computer loading, the tracking filters of the OMEGA program remain active to reduce the time to obtain a valid OMEGA position fix when reactivated. The program provides a continuous display of position, has the capability of automatically switching to a degraded rate aiding source in the event of sensor failure and has been integrated into the P-3C navigation routines with minimal program changes.

Flight test of the P-3C Update OMEGA system has shown radial fix accuracies for straight and level flight of [illegible] feet and 2,608 feet one sigma (standard deviation) for four and three stations with inertial rate aiding velocity. In the degraded mode of air mass rate aiding, radial fix accuracies for straight and level flight are 4,015 feet and [illegible],167 feet one sigma for three and two stations. With no rate aiding source and four stations utilized in fixing, a one sigma error of 12,[illegible] feet was obtained. The standard deviation of radial velocity error was 1.756 knots and [illegible].117 knots for four and three stations with inertial velocity as a rate aiding source, and 2.347 knots and 5.566 knots in the degraded mode utilizing air mass as a rate aiding source with three and two station fixing. Finally, a radial velocity error of 53.383 knots, one sigma where four station no rate aiding mode is utilized. Aircraft maneuvering does not degrade the OMEGA position fix but a substantial degradation in velocity has been observed.

Future work with the laboratory replay program will determine the time to reach stability and the accuracy of the OMEGA position fix at stability, for each of the rate aiding sources and number of stations utilized. Evaluation of hardware and software changes which can increase performance and accuracy will be evaluated by using the laboratory replay and simulation programs.

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